NONDESTRUCTIVE TESTING OF ROPES USING THE TRANSVERSE IMPULSE VIBRATION METHOD

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INTRODUCTION

Rope consists of a group of strands of fibers or wires, twisted or braided together in various constructions and sizes [1,2]. Fibers used for fabrication of synthetic ropes are made of various polymers including nylon, aramid, polyester, and polyethylene. Wires used for fabrication of wire ropes are typically made of carbon steel. Other metals such as stainless steel and monel are also used for wire materials.

Rope is widely used as a flexible tension member in engineering applications such as cranes, tramways, elevators, mine hoists, suspension bridges, offshore platforms, mooring lines, and guy lines. During use, a rope is subjected to abrasion, wear, corrosion, fatigue, and/or accidental damage due to, for instance, overloading or heat. As a result, broken fibers or wires, broken strands, missing materials, and/or diameter reduction develop in the rope [1,2]. Consequently, the strength of the rope degrades with use, compromising its safety and structural integrity. Since failure of rope could result in extensive damage, periodic inspection of the rope for defects is mandatory.

Various nondestructive evaluation (NDE) methods have been applied for inspection of ropes; these include visual, radiographic (with x-or gamma-rays), ultrasonics, acoustic emission, and magnetic [3-8]. The visual method is the simplest, but is tedious, slow, subjective, and limited to surface flaw detection [3,4]. Radiography is applicable to detection of localized flaws; however, it is also slow and expensive. Ultrasonics has very limited applicability because of the complex geometry and construction of the rope which not only pose a transducer coupling problem, but also severely impair the wave propagation in the rope. The acousto-ultrasonic technique based on the so-called stress wave factor has shown feasibility [7,8]. This method may be used to detect localized flaws or to measure the load applied to the rope; however, this method is also very slow and is difficult to implement. Acoustic emission [5,6] can be used to monitor ongoing breakage of wires or fibers; however, it cannot be used for detection of existing defects. The magnetic method is capable of detecting localized flaws and the reduction in the metallic cross-section [3,4]. The magnetic method requires that either the rope be run through the magnetic test device or the magnetic test device be hauled along the rope; in the latter case, the inspection is slow. The weight and attraction of the magnet to the rope under inspection can present operating difficulties. In addition, the magnetic method is limited to inspection of wire ropes made of ferromagnetic materials. Because of these various limitations, the known methods have not met the need for NDE of ropes. NDE methods that are fast, reliable, easy-to-use, and applicable to inspecting ropes made of any material are desired.

Recently, a new approach for NDE of ropes has been developed and its feasibility been demonstrated experimentally [9]. This method, called the transverse impulse vibration method, uses the propagation properties of a vibrational wave produced by applying a transverse impulsive force to a rope. The method can detect localized flaws and determine the load level in the rope. The method can also inspect a long rope (several hundred feet) within several seconds from a single location. In this paper, the principle of the method is described along with some of the experimental results obtained from samples of wire rope up to 1/2 inch diameter and synthetic rope up to 1 inch diameter.

TECHNICAL BACKGROUND

The principle of the transverse impulse vibration method is based on the well-known behavior of the wave motion of a stretched, flexible string [10,11]. When a string is transversely displaced locally by applying an impulsive force, the resulting displacement travels along the string like a wave (designated as a transverse impulse vibrational wave). The wave travels with the velocity, V, which is given as

$$V = (F/m)^{1/2} \tag{1}$$

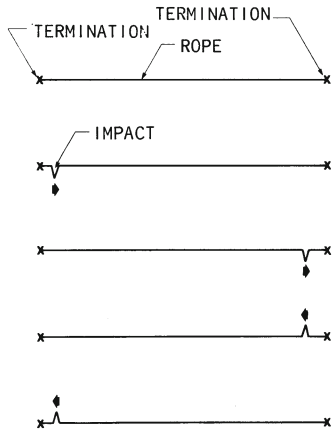
where F is the applied tension (or load) and m is the mass per unit length of the string. If the wave encounters a boundary across which the mechanical impedances are different, a partial reflection of the wave occurs. The reflection coefficient, R, of the wave traveling from region 1 with the mechanical impedance Z_1 to region 2 with the mechanical impedance Z_2, is given as

$$R = (Z_1 - Z_2)/(Z_1 + Z_2) \tag{2}$$

where $Z = (Fm)^{1/2}$. The possible values of R range from -1 to +1. A negative R means that the wave is inverted (180-degree phase shift) when it is reflected.

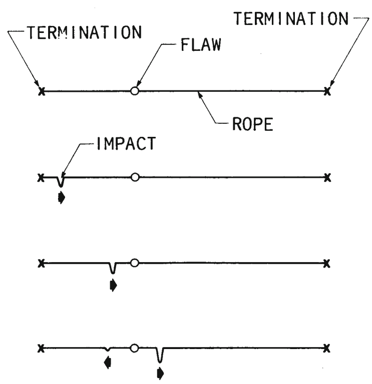
The propagation behavior of a transverse impulse vibrational wave on a rope terminated at both ends is illustrated in Fig. 1. The initial impulse is produced by applying an impulsive force transversely to the rope (Fig. 1b). The wave propagates along the length of the rope until it reaches the termination (Fig. 1c). At the termination, the wave is reflected with a 180-degree phase shift (R at the termination is -1 because $Z_2 \gg Z_1$) and propagates backward until it reaches the other termination (Fig. 1d and 1e). The process is repeated, and the wave travels back and forth along the rope until all of its energy is dissipated.

When a flaw is present in a rope, the wave propagated along the rope (Fig. 2c) is partially reflected at the flaw while the transmitted portion of the wave continues propagating along the rope (Fig. 2d). Each of the reflected and transmitted waves travels back and forth along the rope and produces a partially reflected wave whenever it passes



PROPAGATION OF IMPULSE
WAVE ON A ROPE

Fig. 1. Propagation of an impulse wave on a rope with no flaw



PROPAGATION OF IMPULSE WAVE
ON A ROPE WITH A FLAW

Fig. 2. Propagation of an impulse wave on a rope with a flaw

the flaw. The resulting pattern of the wave propagation is further described in the experimental results and discussion section.

With the transverse impulse vibration method, the motion of wave propagation is monitored by placing an appropriate displacement, vibration, or acceleration sensor near one end of a rope and recording the motion of the rope at that location as a function of time. From the signal, the transit time (or velocity) of the wave is measured and is used to determine either the load level or the mass per unit length of the rope (which can be used as an indicator of wear and corrosion). The partially reflected signals from flaws such as broken strands or regions of reduced cross-section are then detected by the sensor.

INSTRUMENTATION

A schematic diagram of the instrumentation for NDE of ropes using the transverse impulse vibration method is illustrated in Fig. 3. An impulsive transverse force was applied to a rope by using a device such as a pneumatically actuated hammer or a tapping rod. The wave thus generated was sensed by using a laser displacement sensor or electromagnetic vibration sensor placed near one end of the rope. The detected signal was amplified, conditioned, and then recorded on an digitizing oscilloscope for display, storage, and analysis.

EXPERIMENTAL RESULTS AND DISCUSSION

Signals from Ropes Containing No Flaws and Measurements of the Velocity of Wave Propagation

An example of signal patterns obtained using the transverse impulse vibration method from a rope containing no flaws is shown in Fig. 4. The signal in Fig. 4 was detected from a 45-foot long, 1/4-inch diameter, double-braided nylon rope using a laser displacement sensor. Since the wave travels back and forth along the length of the rope, repeated end-reflected signals were detected as shown in Fig. 4.

Examples of the wave velocity as a function of the applied load (or tension), determined by dividing the rope length by the corresponding transit time measured from the detected signals, are plotted in Fig. 5 (triangles). Calculated values using Eq. (1) are also shown in Fig. 5 (solid lines). Fig. 5a is from a 1/4-inch diameter, double-braided nylon rope and Fig. 5b is from a 45-feet long, 1/2-inch diameter, steel wire rope with fiber core. The wire rope contained 6 strands with each strand made up of 37 wires. As shown in the figures, the agreement between the measured and calculated values is very good.

From the velocity measurements and using Eq. (1), one can determine either the load level, F, in the rope or the mass per unit length, m, of the rope, if the other parameter is known. If both are unknown, they can still be determined by making two velocity measurements before and after applying an additional load of known amount to the rope. Since the velocity can be determined very accurately (within a few tenths of a percent error), the parameters F and m can also be determined accurately. Since, m = density x pi x diameter^2/4, the density or diameter of the rope, which indicates the loss of material from corrosion and wear, can also be determined from the velocity measurements.

Signals from Ropes Containing a Localized Flaw

Examples of signals obtained from flawed ropes are shown in Figs. 6(a) through (c). These were acquired by introducing a localized flaw at about the midpoint of, respectively, 1/4-inch and 1-inch diameter, double-braided, nylon ropes, and the 1/2-inch diameter steel wire rope sample described above.

The flaw signals in Fig. 6(a) and (b) were from a completely severed cover of the double-braided nylon rope; the severed ends of the cover were separated by about 6 and 7 inches, respectively. The flaw in the 1/2-inch diameter wire rope was simulated by cutting a strand and removing an approximately 12-inch long piece of the strand. As shown in the figure, these simulated flaws produced readily detectable, partially reflected signals. The data shown in Fig. 6 clearly demonstrate the feasibility of the method to detect discrete flaws.

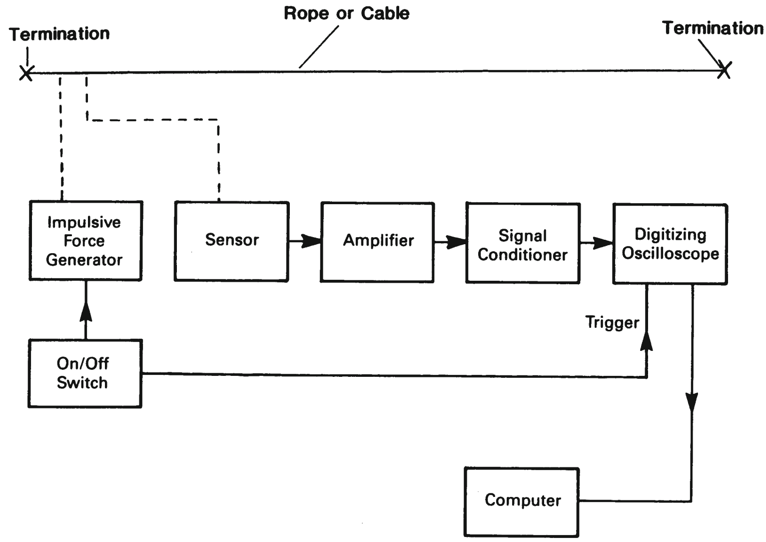


Fig. 3. Schematic diagram of the instrumentation for the transverse-impulse vibration method

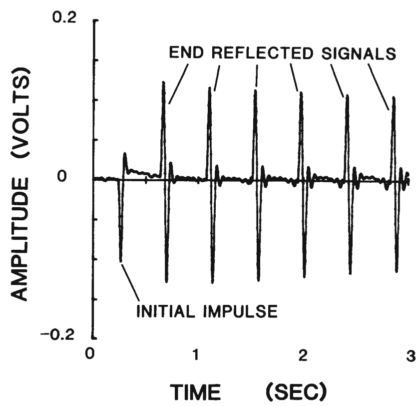
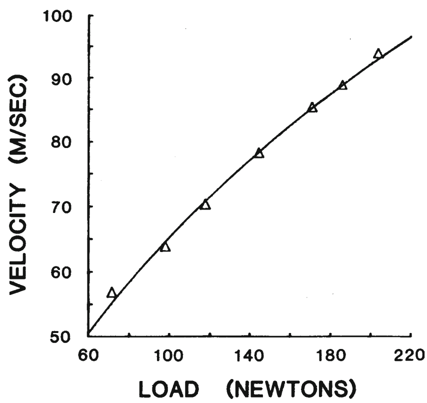
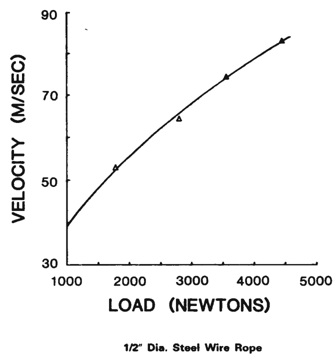


Fig. 4. Example of signal patterns obtained from a rope with no flaw. The signals are from a 45-foot long, 1/4-inch diameter nylon rope.

Additionally, the amplitude of the flaw signal in Fig. 6 increased with time upon successive reflections from the end of the rope. The reason for this increase is schematically illustrated in Fig. 7. The initial impulse introduced near end (termination) A propagates along the rope and is reflected back and forth between the rope ends (solid line in the upper portion of the figure). When the initial wave passes the flaw, it also produces a flaw signal which travels back and forth along the rope (beaded line). On the first return trip of the initial wave, it is



(a)



(b)

Fig. 5. Velocity of wave propagation vs. load: (a) 1/4-inch diameter, double-braided, nylon rope, and (b) 1/2-inch diameter, steel wire rope with fiber core. Triangles are experimentally measured values and solid line is calculated values.

again partially reflected at the flaw, producing another flaw signal which travels toward end B and subsequently moves back and forth along the rope (dashed line). During the second round trip, the initial wave again produces a flaw signal on each of its forward and return trips (represented by the second beaded and dashed lines, respectively, in the figure). Since the second production of the flaw signal coincides with the arrival of the previously produced flaw signal, the two signals add together. This process is repeated, resulting in the increase of the flaw signal amplitude with time, as depicted in the lower portion of Fig. 7. (When the partially reflected wave passes the flaw, it also produces its own partially reflected wave. These waves are not considered in Fig. 7 for the sake of simplicity.) When the flaw is located at the midpoint of

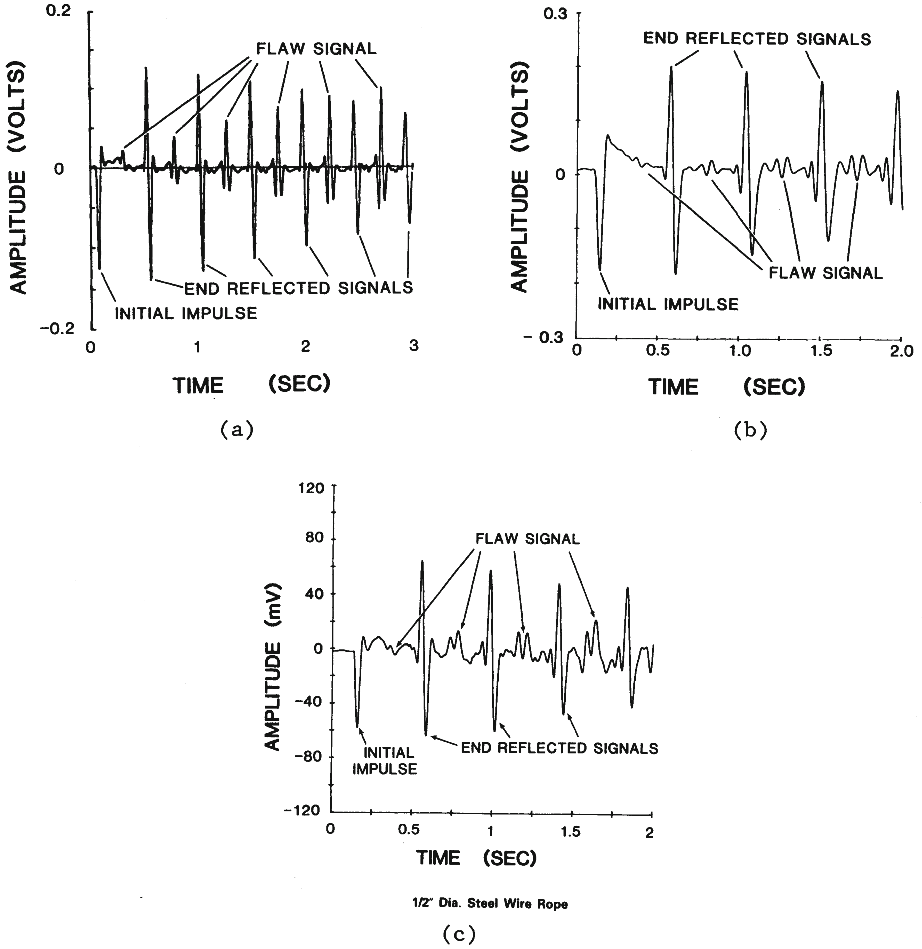


Fig. 6. Signal pattern obtained from ropes with a localized flaw at midpoint of the rope length: (a) 1/4-inch diameter, double-braided, nylon rope, (b) 1-inch diameter, double-braided, nylon rope, and (c) 1/2-inch diameter steel wire rope

the rope length, the flaw signals produced on the forward and return trips add together, thus further enhancing the effect. The data shown in Fig. 6 fall in this category. This self-amplification of the flaw signal is unique and should be useful in detecting small flaws.

The results of the limited feasibility studies conducted so far indicate that the flaw signal is dependent on the magnitude of the impedance mismatch and the length of the flaw. Also, the size of a flaw that produced readily observable flaw signals was about 7 to 8 percent mismatch in impedance with a length of about 10 times the rope diameter. The detectability of smaller flaws should be improved by adapting signal processing techniques such as averaging, spatial compounding, or split-spectrum, [12] or by improving instruments for signal excitation, sensing, and data acquisition. Since the wave travels along the whole length of a rope, the detected signals contain all the information on the conditions of the rope. Finding ways of extracting from the detected signals suitable information for determining the structural integrity of rope should be the objective of further research.

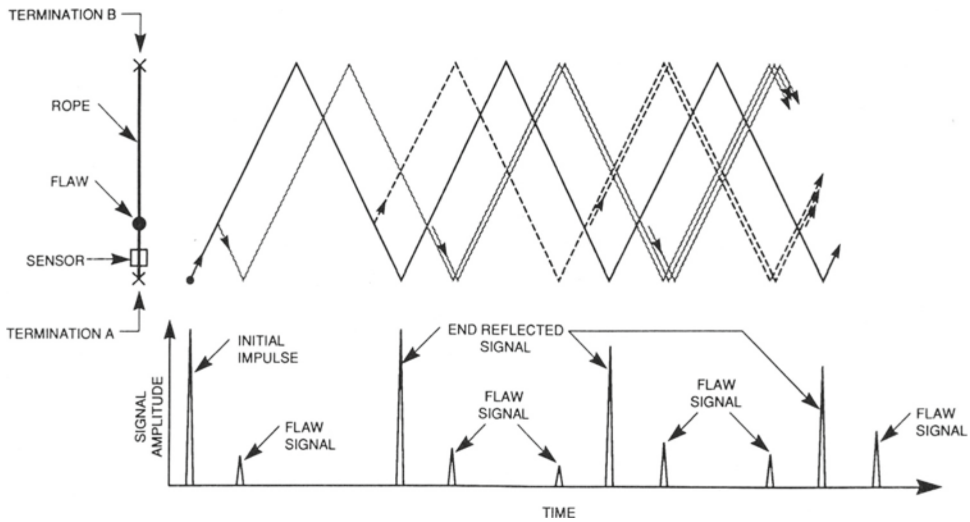


Fig. 7. Wave propagation along the rope and production of flaw signals and resulting signal pattern as a function of time. Solid line indicates propagation of the initial impulse. Beaded and dashed lines indicate propagation of the partially reflected wave at the flaw during the trip of the initial impulse from termination A to B, and from termination B to A, respectively.

CONCLUSION

The transverse impulse vibration method for NDE of ropes can be used for determining the load level and/or the mass per unit length of the rope. The latter in turn can be used to determine the overall wear or corrosion condition. The method can also be used to detect localized flaws. Inspections can be performed within a short time (several seconds) over a long rope (several hundred feet) made of any material whether it is metallic or nonmetallic. With further research and development, the method will provide a simple, fast, and reliable means for NDE of ropes.

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